Cainozoic Stratigraphy at Wellington Caves, New South Wales

R. A. L. OSBORNE

A sequence of Cainozoic sediments infills karst cavities of the Devonian Garra Formation at Wellington Caves, N.S.W. The sequence is divided into two formations, the older Phosphate Mine Beds and the younger Mitchell Cave Beds. These are subdivided into informal lithostratigraphic units.

The Phosphate Mine Beds are composed of laminated clays, phosphorites, and indurated entrance facies deposits, along with osseous sandstones and conglomerates deposited by turbidity currents in a nothephreatic environment. The Mitchell Cave Beds consist of entrance facies and bone breccia.

An unconformity separates the two formations, and has a complex geometry. It is the product of a period of phreatic speleogenesis that excavated cavities within the Phosphate Mine Beds. The Mitchell Cave Beds infill these cavities. The Mitchell Cave Beds are most likely Pleistocene-Recent in age while the Phosphate Mine Beds may extend back into the Tertiary.

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INTRODUCTION

The Wellington Caves, located 8 km south of the town of Wellington in central western N.S.W. (Fig. 1), have attracted scientific attention since Cainozoic vertebrate fossil remains were first discovered in them during the 1830s. The history and significance of these discoveries has been outlined by Lane and Richards (1963) and Dugan (1980). More recently Dawson (1982) has re-examined fossil material held in museum collections.

Seven significant caves — Cathedral, Gaden-Coral, Mitchell, Gas Pipe, Lime Kiln, Triplet, and Water; and three large man-made excavations — Phosphate Mine, Big Sink, and Bone Cave, are located in an area less than 50,000 m^2 (Fig. 1).

The major excavations and all but three of the caves were surveyed and described in detail by Frank (1971). Of the remainder, Water Cave, (now inaccessible) was described by Trickett (1906), Lime Kiln Cave by Osborne *et al.* (1981) and Triplet Cave by Osborne (1982).

The caves have developed as a result of nothephreatic solution in massive limestone of the Garra Formation while the excavations, along with many vertical blind shafts, are the result of phosphate mining (Carne, 1919) and palaeontological excavation.

Colditz (1943) first investigated the relationship between cave development and local geomorphic history. Following Colditz's approach, Frank (1971) related cave development to the inferred capture of the Bell River by Catombal Creek. Frank's conclusions suggested that the caves formed during the Pliocene. Francis (1973) questioned the basis of Colditz's work and suggested a Miocene age for the caves based on the radiometric ages of basalts near Stuart Town.

Sediment, rather than limestone, forms the floors of most of the caves. By excavating shafts to depths of 11.5 m in Mitchell Cave and 11 m in Cathedral Cave in search of vertebrate fossils, Ramsay (1882) demonstrated that the sediment had a considerable thickness. Most of the strata described here are exposed in the Phosphate Mine where mine passages are excavated through an almost completely sediment-filled cave.

Fig. 1. Location. Semicircles with dots are limestone cave localities.

Despite 150 years of palaeontological research at Wellington Caves the only previous stratigraphic study of the Cainozoic deposits is that of Frank (1971) who proposed a division into three units with a number of sub-units. The stratigraphy is found here to be more complex than Frank's interpretation, with at least three unconformities and a possible disconformity in the succession.

The letters USGD and SUP followed by a five digit number refer to specimens housed in the petrological and the palaeontological collections respectively of the Department of Geology and Geophysics, University of Sydney.

STRATIGRAPHY

The Cainozoic sequence unconformably overlies and is partly enclosed within massive limestone of the Devonian Garra Formation (Strusz, 1965). A maximum stratigraphic thickness of 37 m has been measured. The stratigraphy is summarized in Fig. 2.

A. *Phosphatic rim rock*

This white phosphatic deposit is up to 300 mm thick and encrusts bedrock (Devonian Garra Formation) cave walls and ceilings. It is only developed in Phosphate Mine, Big Sink and Bone Cave. The phosphatic rim rock is laminated parallel to the
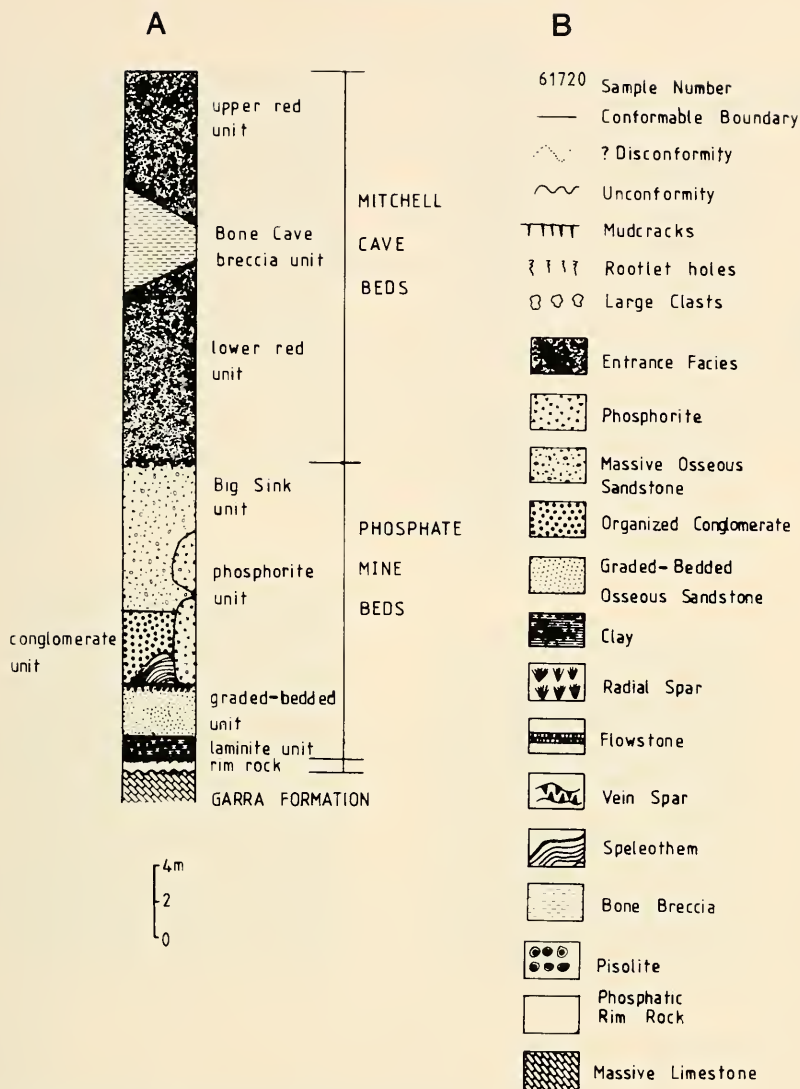
A

B

61720	Sample Number
——	Conformable Boundary
	? Disconformity
∿∿	Unconformity
⊤⊤⊤⊤	Mudcracks
⸮ ↑ ↑⸮	Rootlet holes
◌ ◯ ◌	Large Clasts
	Entrance Facies
	Phosphorite
	Massive Osseous Sandstone
	Organized Conglomerate
	Graded-Bedded Osseous Sandstone
	Clay
	Radial Spar
	Flowstone
	Vein Spar
	Speleothem
	Bone Breccia
	Pisolite
	Phosphatic Rim Rock
	Massive Limestone

Column A labels (top to bottom): upper red unit; Bone Cave breccia unit; lower red unit; Big Sink unit; phosphorite unit; conglomerate unit; graded-bedded unit; laminite unit; rim rock; GARRA FORMATION. Right bracket labels: MITCHELL CAVE BEDS; PHOSPHATE MINE BEDS. Scale: 4m / 2 / 0.

Fig. 2. **A**: Stratigraphy. **B**: Key for stratigraphic columns.

surfaces to which it adheres making its boundaries with both the Garra Formation and the Phosphate Mine Beds unconformable.

B. *Phosphate Mine Beds*

The Phosphate Mine Beds are a sequence of laminated clays, osseous sandstones, conglomerates, and phosphorites exposed in Big Sink, Phosphate Mine and Bone Cave. They take their name from the Phosphate Mine in which they are best exposed. Neither a complete section nor the base of the formation is exposed. A composite section (Fig. 3) is formed from exposures in the Phosphate Mine and Big Sink (localities 1, 4, and 7, Fig. 8).

The Phosphate Mine Beds are divided into five informal lithostratigraphic units.
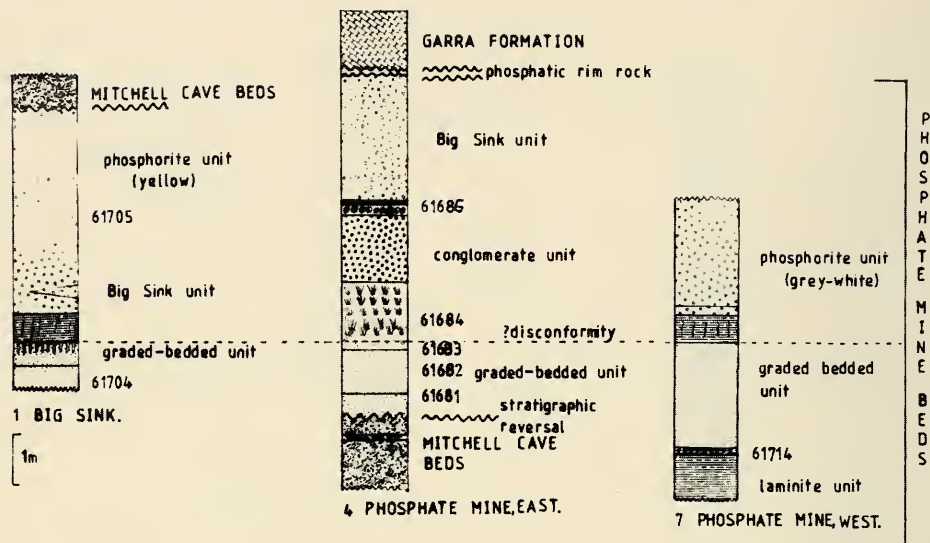
Fig. 3. Phosphate Mine Beds, composite type section.

B.1. *Laminite unit*

This unit, of which 1.3 m is exposed, consists of laminated clays with well-developed mud cracks. Spar has been deposited between laminae and in mud cracks sometimes resulting in brecciation. The top of the unit is marked by a bed of very pale yellow laminated clay.

Laminae range in thickness from a few millimetres to 15 mm. Unlike the 'cap muds' of Bull (1977) and the 'layered clay fill' of Osborne (1978) the laminae represent periodic deposition of similar material rather than distinct compositional changes. X-ray diffraction study of USGD 61698, 61699 (Fig. 5) and 61714 (Fig. 3) indicated that the main component is quartz along with a kandite phase, probably kaolinite.

Finely laminated clays are the product of a stable, low energy environment. In caves they may be deposited in pools perched above the water table or in a low energy phreas like that described as a nothephreas by Jennings (1977). Since laminated clays occur with the same stratigraphy at widely separated parts of the Phosphate Mine it seems most likely that they were deposited in the phreas. Desiccation features indicate variations of the water table level at the time of deposition.

B.2. *Graded-bedded unit*

The graded-bedded unit conformably overlies the laminite unit and consists of 2.7 m of well-cemented, graded sandstone beds up to 170 mm thick interbedded with thin parallel-laminated, ripple-laminated, and mud-cracked horizons (Fig. 4A). The top of the unit is marked by a bed with prominent mud cracks, 80 mm deep, filled with

Fig. 4. **A**: Graded bedded unit exposed in wall of Phosphate Mine at locality 11, Fig. 8. Note mudcracks and laminated bed. Lens cap 55 mm in diameter. **B**: Graded bedded unit exposed in wall of Phosphate Mine at locality 2 Fig. 8. Note phosphate filled 'rootlet' structures. **C**: Polished block of osseous sandstone from the graded bedded unit, USGD 61704, Fig. 3. Note lower graded bed and upper laminated bed. Scale bar 10 mm. **D**: Polished block of thin graded bed from the graded bedded unit, USGD 61697, locality 11, Fig. 8. Scale bar 5 mm. **E**: Polished block of ripple laminated bed from the graded bedded unit, USGD 61695, Fig. 5. Scale bar 10 mm.
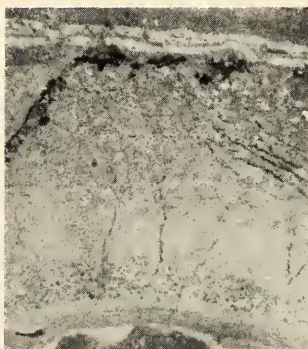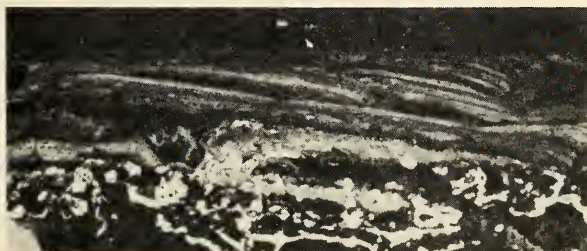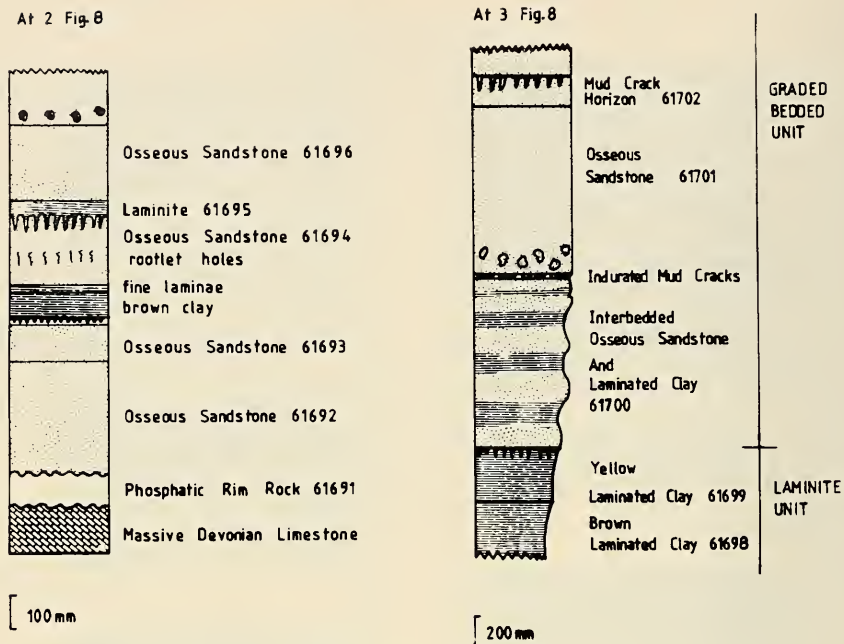
A

B

C

D

E

At 2 Fig. 8

Osseous Sandstone 61696

Laminite 61695
Osseous Sandstone 61694
rootlet holes
fine laminae
brown clay

Osseous Sandstone 61693

Osseous Sandstone 61692

Phosphatic Rim Rock 61691

Massive Devonian Limestone

⌐ 100 mm

At 3 Fig. 8

Mud Crack
Horizon   61702

Osseous
Sandstone   61701

Indurated Mud Cracks

Interbedded
Osseous Sandstone
And
Laminated Clay
61700

Yellow
Laminated Clay 61699

Brown
Laminated Clay 61698

GRADED
BEDDED
UNIT

LAMINITE
UNIT

⌐ 200 mm

Fig. 5. Graded bedded unit, sections in Phosphate Mine.

opaline phosphatic speleothem. Within the unit are vertical tubes filled with phosphate (Fig. 4**B**) interpreted by Frank (1971) as invertebrate burrows. Piearce (1975) has shown invertebrates can produce casts and burrows in cave sediments, but since tree roots presently penetrate sediments in the Phosphate Mine, it seems more likely that these structures are phosphate-filled rootlet holes.

The relationships between the various types of beds are shown in Figs 4 and 5. In Fig. 4**C** a graded sand bed is overlain by a bed of parallel-laminated mud, Fig. 4**D** is of

Entrance Facies Deposits   Water   ▼ Speleothem

V
A
D
O
S
E
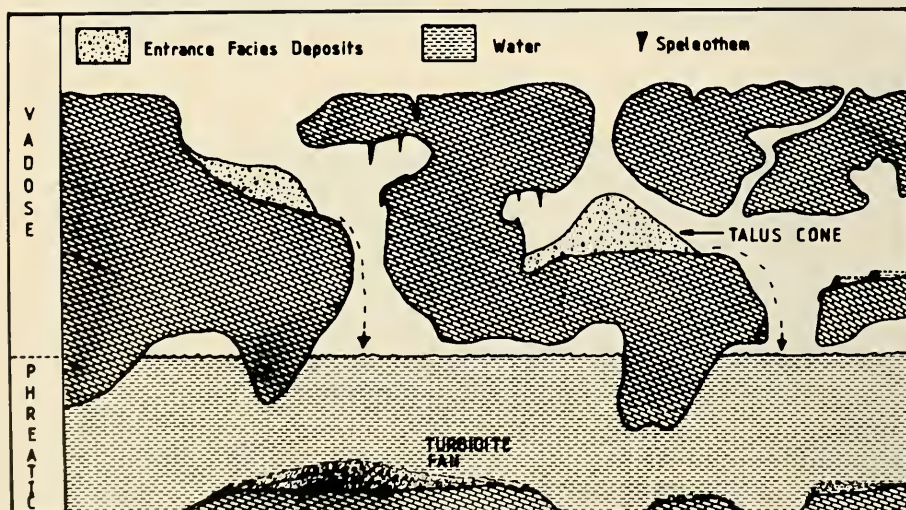
P
H
R
E
A
T
I
C

TALUS CONE

TURBIDITE
FAN

Fig. 6. Deposition of turbidites in caves.

a thin graded bed only 10 mm thick, while Fig. 4**E** shows ripple- and convolute-laminated beds.

These structures are similar to those found in classic turbidites (Bouma, 1962) and suggest that turbidity currents may have been the depositional agents for the graded-bedded unit. Turbidity currents have usually been invoked for the deposition of coarse clastics in deep water environments. They were first recognized in inland lakes and reservoirs (Grover and Howard, 1938) where turbid flood waters interacted with less dense ponded water.

Similar conditions to those in lakes can exist in caves. Where a nothephreas is separated from the surface by air-filled caves (Fig. 6) coarse sediments will be trapped in talus fans, so that under normal conditions only fines will reach the phreas. Where such caves do not have active vadose streams (as is the present case at Wellington Caves) coarse clastics will only reach the phreas as a result of either slumping or flood rains. These will both result in the rapid introduction of sediment into the phreas and may produce turbidity currents. Due to the network geometry of nothephreatic caves a turbidity current is likely to cause deposition some distance from its point of initiation.

Osseous sandstone

The sandstones of the graded-bedded unit have their sand fraction composed almost entirely of bone and tooth fragments, and are therefore described as *osseous sandstones*.

Osseous sandstones are hard, light tan-coloured rocks with large spar crystals visible to the naked eye on broken surfaces. In thin section three main components are recognized: bone and tooth fragments, equant spar and clay (Fig. 7**A**).

Fragments include long bone (which may be up to 5 mm long), membrane bone and enamel. In polished blocks bone fragments appear as elongate dark specks which are oriented parallel to bedding. Heads of long bones often display complex involute textures, while marrow cavities of long bones are filled with spar. In thin section under plane polarized light bone fragments are pale yellow in colour. They have a low birefringence and a longitudinal fibrous structure resulting in irregular extinction. Small dark spots on fragments of long bone mark the ends of the canaliculi (Fig. 7**A**).

Two types of carbonate cement occur in osseous sandstones. Equant spar, the more common type, forms crystals up to 2 mm in section with most falling in the range of 0.5 to 1 mm. Equant spar is a secondary cement, filling spaces between bone fragments and replacing clay. In some cases (USGD 61681, Fig. 3) the clay has been reduced to thin coatings on bone fragments. The other type of carbonate cement is acicular plumose cement which is found both in brecciated phosphorite and osseous sandstones.

Brecciated phosphorite from the entrance to Bone Cave (USGD 61690) contains acicular plumose cement which forms an iron-stained rim around the outside of clear equant spar crystals (Fig. 7**B, C**). The plumose rim and the clear equant spar extinguish together between crossed polars. Where plumose cement occurs without an equant spar centre it extinguishes in large masses that behave in a similar way to equant spar grains. Osborne (1978) reported acicular plumose cement from deposits in Cliefden Caves and believed it to consist of calcite pseudomorphs after subaqueously precipitated aragonite. It seems likely that equant spar cement is produced by neomorphism of acicular plumose cement.

Phosphates occur as minor, secondary vadose cements in osseous sandstones with collophane and, to a lesser degree, dahllite filling mud cracks and voids. In USGD 61693 (Fig. 5) botryoidal masses of collophane with rims of dahllite surround and are embayed into equant spar grains. In USGD 61695 (Fig. 5) collophane has invaded
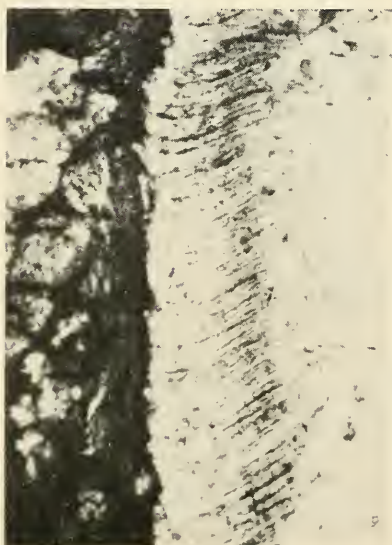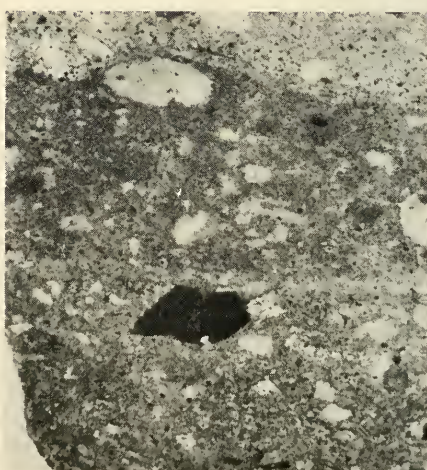
Fig. 7. **A**: Thin section of osseous sandstone, USGD 61704, Fig. 3, crossed nicols, x63. Note bone fragments, light grey. Black dots on bone fragments are canaliculi. **B**: Thin section of brecciated phosphorite, USGD 61690, from the Bone Cave entrance, crossed nicols, × 63. This shows a zone at the edge of a large spar crystal. Note acicular plumose structure. **C**: USGD 61690, plane polarized light, × 130. Shows plumose edge zone of spar. **D**: Polished block of conglomerate from the conglomerate unit, USGD 61706, locality 5, Fig. 8. Note alignment of clasts. Scale bar 10 mm.

TABLE 1

Point Counts of Osseous Sandstones

Sample	Bone Fragments	Spar	Clay	Phosphate	Others	Total Points
61681	55%	31%	14%	—	—	954
61693	47%	10%	17%	26%	—	834
61704	40%	23%	23%	12%	2%	1671

between equant spar grains while in USGD 61700 (Fig. 5) a vein is filled first with collophane, then with dahllite and finally with spar.

Point counts of osseous sandstones, Table 1, show bone fragments forming up to 55% of the rock. Such high concentrations require a significant source of bone in the caves prior to deposition.

Deposits of bones are not uncommon in caves. Small bone fragments are found as undigested residue in the faeces of carnivorous mammals and in pellets regurgitated by birds of prey. Kukla and Lozek (1958) note that owls can produce extensive deposits of bone. Unlike the bone in the osseous sandstone this bone is usually not broken (Lundelius, 1966). Since the fragments in the osseous sandstone are of small bones they were probably introduced into the caves by small carnivores. Transport and re-deposition may have been responsible for breakage of membrane bones but is unlikely to have resulted in the observed breakage of long bones.

B.3. *Conglomerate unit*

The 4 m-thick conglomerate unit overlies the graded-bedded unit. Its lower boundary is exposed at two places in the Phosphate Mine (localities 4 and 5, Fig. 8). At locality 4 the conglomerate unit is separated from the graded bedded unit by 830 mm of speleothem while at locality 5 the conglomerate unit overlies the mud-cracked horizon at the top of the graded-bedded unit. Both the mud cracks and the speleothem suggest that the lower boundary of the conglomerate unit may be disconformable.

The conglomerate is poorly sorted, consisting of horizontally aligned angular fragments of clay, phosphatic mudstone, bone and teeth in a porous matrix in which birdseye structures are developed (Fig. 7D). In thin section (USGD 61707, locality 5, Fig. 8) the matrix is seen to consist of blocky spar, clay, fine bone fragments, and small clasts of phosphatic mudstone. X-ray diffraction indicated that quartz and hydroxyapatite are the main non-carbonate phases present.

Like the graded-bedded unit, the conglomerate unit was probably deposited by turbidity currents in the phreas, the larger grain size resulting from deposition close to the point where clastics entered the phreas. This is equivalent to the inner fan area proposed by Walker (1975) as the locus of deposition for re-sedimented conglomerates with a preferred clast orientation.

B.4. *Phosphorite unit*

Three types of phosphorite — grey-white, yellow, and brecciated — occur within the sequence at about the same stratigraphic level. Grey-white phosphorite overlies the graded-bedded unit in the western part of the Phosphate Mine (Fig. 3). Yellow phosphorite overlies the graded-bedded unit and has Big Sink unit interbedded with it in Big Sink, while brecciated phosphorite is overlain by Big Sink unit at the entrance to Bone Cave.

In the Bat Chamber of the Phosphate Mine and at the northern end of the Main Drive, sheets of phosphatic speleothem have blocked off sections of the cave,
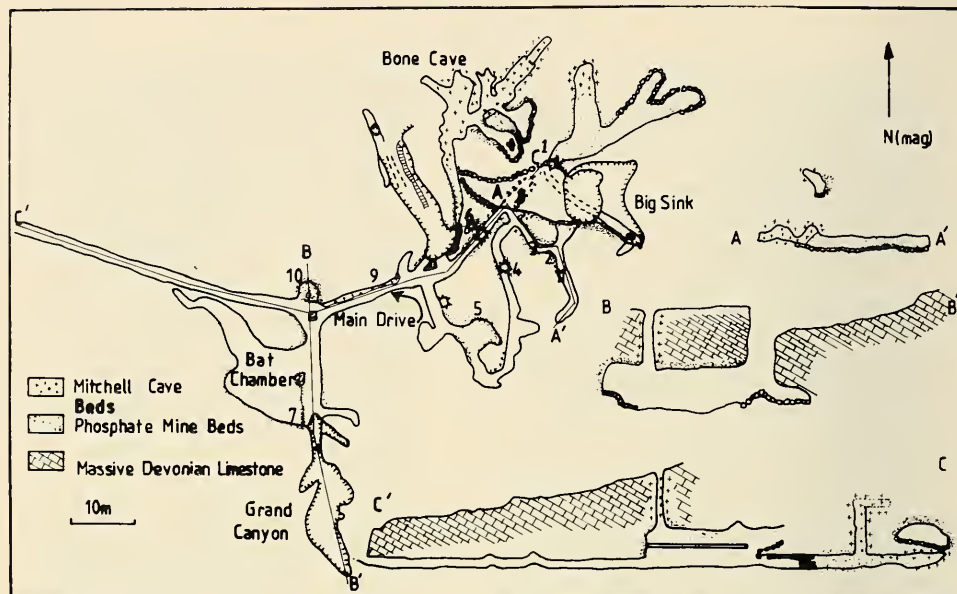
Fig. 8. Phosphate Mine, Bone Cave and Big Sink. Plan and sections after Frank (1971).

preventing the deposition of grey-white phosphorite. In these pockets are complex non-clastic sediments that appear to be time equivalents of the grey-white phosphorite.

The three types of phosphorite and the non-clastic sediments are grouped together to form the phosphorite unit which is considered to be a lateral equivalent of the conglomerate and Big Sink units.

B.5. *Big Sink unit*

The Big Sink unit is the uppermost unit of the Phosphate Mine Beds and takes its name from Big Sink where an 8 m section is exposed, forming the southern wall of the doline. It is also exposed in Bone Cave, the Phosphate Mine, in a small subsidence doline near the entrance to Bone Cave (locality 6, Fig. 8) where it conformably overlies the conglomerate unit, and at the surface in the flat area between Big Sink and the entrance to Bone Cave.

The unit is composed of beds of osseous sandstone interbedded with thin layers of structureless mud. The osseous sandstones are indurated and graded bedding is not developed. Bone and tooth fragments, which may be locally concentrated, are randomly oriented. In some places bedding has a high initial dip, suggesting that the unit consists of cemented entrance facies deposits.

The Big Sink unit is the only unit of the Phosphate Mine Beds readily correlated with the stratigraphic scheme of Frank (1971) being equivalent to his 'Unit 1 BG'.

The Phosphate Mine Beds — Mitchell Cave Beds Boundary

The boundary between the Phosphate Mine Beds and the Mitchell Cave Beds is exposed in the Phosphate Mine, Big Sink and Bone Cave. At the entrance to Bone Cave the Mitchell Cave Beds are surrounded completely by the Phosphate Mine Beds. Further along the entrance passage of Bone Cave the boundary between the formations is vertical (Fig. 9A). In the Phosphate Mine (locality 8, Fig. 8) the boundary is marked by a layer of flowstone separating Big Sink unit from lower red unit. Frank (1971) mapped this boundary but was unaware of its significance. Also in the Phosphate Mine
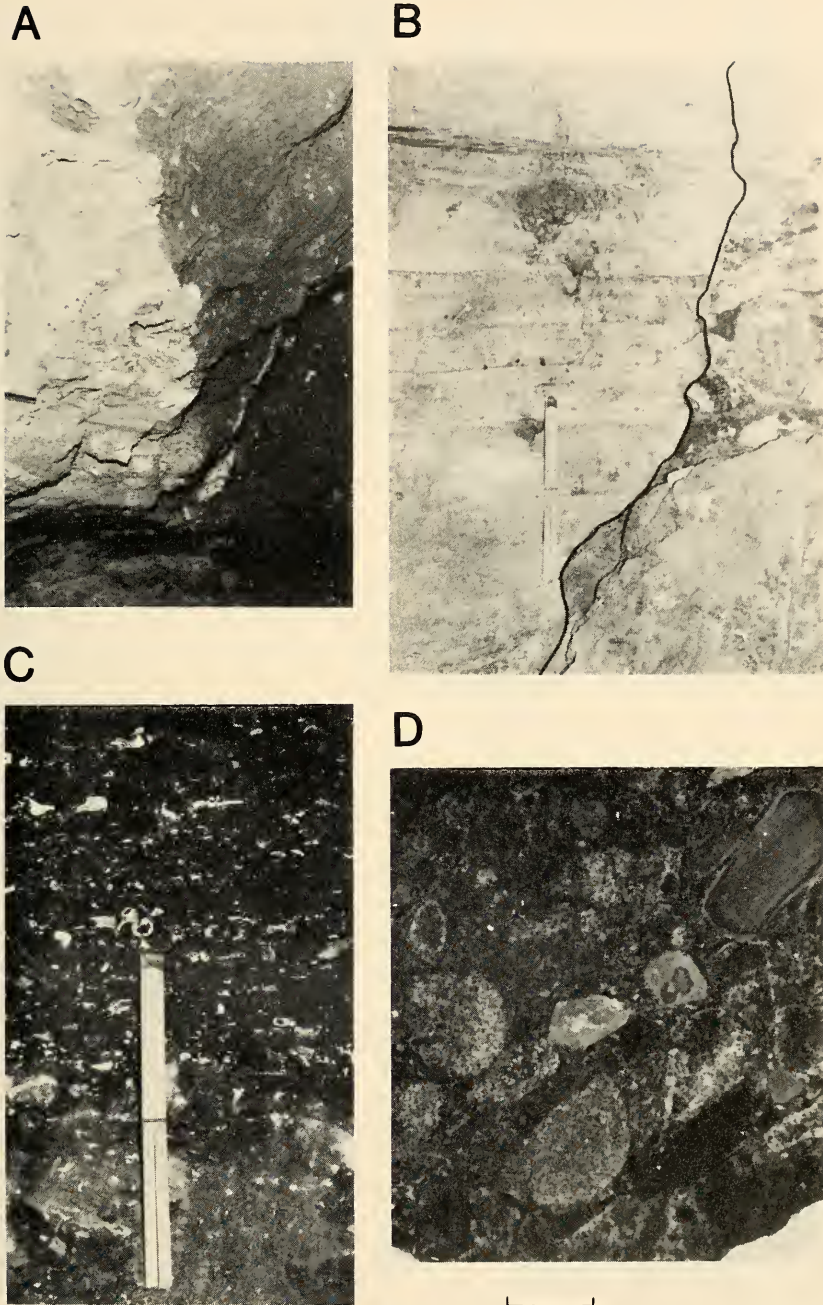
Fig. 9. **A**: Outcrop of unconformity in entrance passage to Bone Cave. Phosphate Mine Beds (grey) are exposed on the left while Mitchell Cave Beds (dark) are exposed on the right. The unconformity surface here is a vertical plane. **B**: Outcrop of unconformity in wall of Phosphate Mine at locality '3' Fig. 8. Unconformity surface is retouched dark line. Graded bedded unit is exposed to the left of the surface and undifferentiated Mitchell Cave Beds to the right. **C**: Bone Cave breccia unit exposed in wall of Bone Cave. Note alignment of bone fragments and large cobbles at base. **D**: Polished block of disorganized conglomerate, USGD 61707, from locality 9, Fig. 8. Scale bar 10 mm.

MITCHELL CAVE BEDS

••••• unconformity 3

graded-bedded unit

laminite unit

—— unconformity 2

phosphatic rim rock

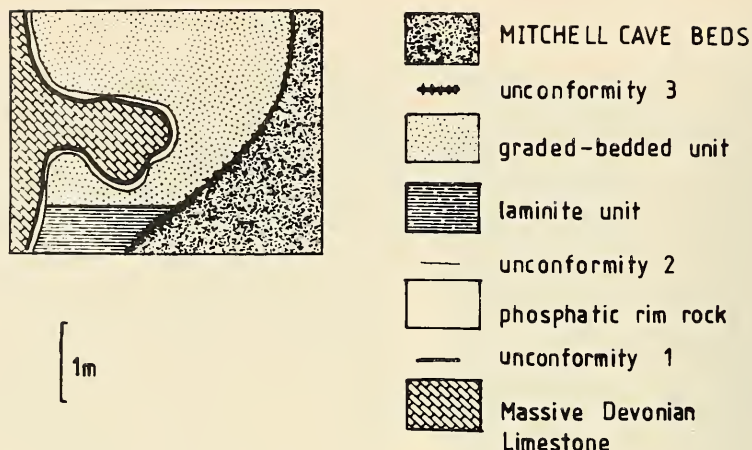—— unconformity 1

Massive Devonian Limestone

1m

Fig. 10. Unconformities exposed in Phosphate Mine at locality 3, Fig. 8.

(locality 3, Fig. 8) a sloping boundary between the graded-bedded unit and the Mitchell Cave Beds is exposed (Figs 9**B**, 10).

The geometry of the boundary between the two formations indicates that they are unconformable and that the Mitchell Cave Beds were deposited in caves that developed within the Phosphate Mine Beds (see idealized cross section through the Phosphate Mine Fig. 11).
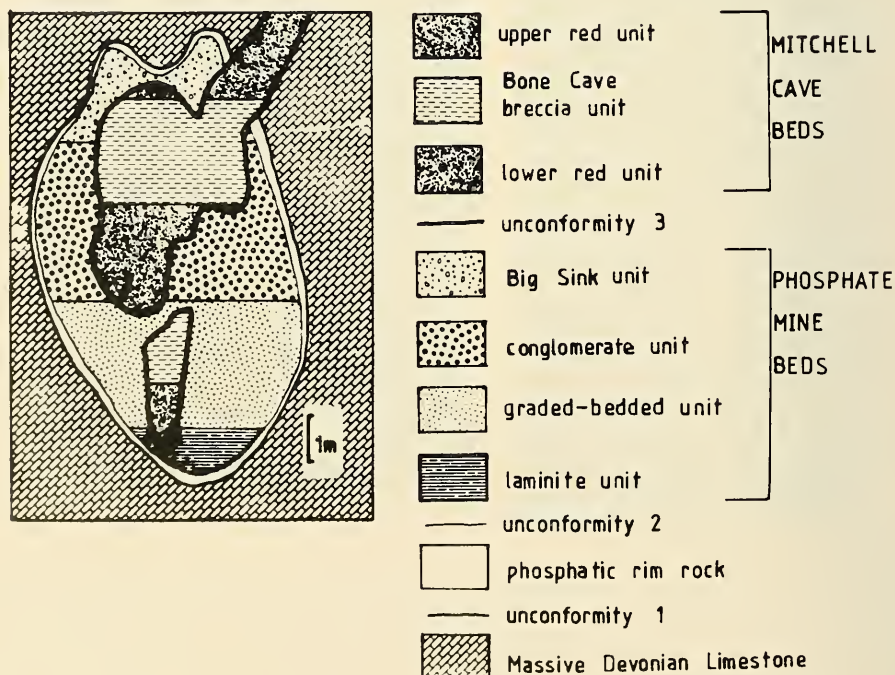

upper red unit   ⎫
                      ⎪ MITCHELL
Bone Cave   ⎬ CAVE
breccia unit   ⎪ BEDS
                      ⎭
lower red unit

—— unconformity 3

Big Sink unit   ⎫
                      ⎪ PHOSPHATE
conglomerate unit   ⎬ MINE
                      ⎪ BEDS
graded-bedded unit   ⎭

laminite unit

—— unconformity 2

phosphatic rim rock

—— unconformity 1

Massive Devonian Limestone

1m

Fig. 11. Idealized section through Phosphate Mine.
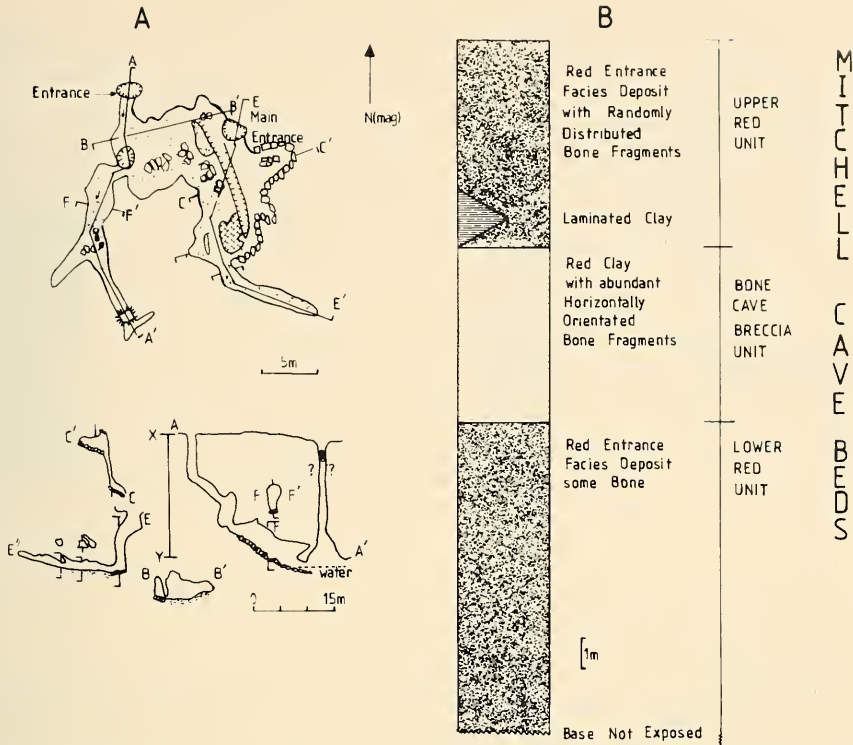
Fig. 12. **A:** Plan and sections of Mitchell Cave after Frank (1971). **B:** Type section for Mitchell Cave Beds.

C. Mitchell Cave Beds

The Mitchell Cave Beds consist of entrance facies deposits and bone breccias. They unconformably overly the Phosphate Mine Beds and take their name from Mitchell Cave where their type section (Fig. 12) is located. They are divided into three informal lithostratigraphic units and are laterally more extensive than the Phosphate Mine Beds. In Bone Cave, Big Sink and the Phosphate Mine, the Mitchell Cave Beds have been deposited in cavities developed within the Phosphate Mine Beds while in Mitchell Cave they directly overlie limestone bedrock.

C.1. Lower red unit

The lower red unit forms the base of the sequence in Mitchell Cave and is also exposed in the Phosphate Mine. It is a red, poorly-consolidated, unbedded entrance facies deposit consisting of sparse bone and tooth fragments in a matrix of red friable clay mainly composed of quartz with a small amount of kaolinite. The lower red unit attains a maximum thickness of 9.2 m in the Mitchell Cave section.

C.2. Bone Cave breccia unit

The Bone Cave breccia unit is named after Bone Cave where a 2 m thick exposure has been the source of much vertebrate fossil material (Lane and Richards, 1963). It is found conformably overlying the lower red unit in Mitchell Cave and the Phosphate Mine and is equivalent to 'Unit 3 R.B.' of Frank (1971).

The unit consists of a partially cemented breccia of bone and tooth fragments (up to 0.25 m long) and limestone cobbles (up to 0.5 m in diameter) in a red clay matrix. The bone fragments are horizontally aligned (Fig. 9**C**). The boundary between the

Bone Cave breccia unit and the Big Sink unit, the wall of the cavity in which the Bone Cave breccia unit was deposited, is exposed in the eastern wall of Bone Cave. The horizontal alignment of the bone and tooth fragments continues undisturbed right up to this boundary.

Numerous theories have been advanced to explain the deposition of this unit with its profusion of bones and teeth. Some theories of historic interest have been outlined by Lane and Richards (1963). Lundelius (1966) proposed that the marsupial 'lion', *Thylacoleo carnifex,* introduced the bones by using the cave as a den. Frank (1971) suggested that the unit was deposited primarily by gravity with some slight contribution by water.

The horizontal alignment of the bone and tooth fragments suggests that the unit is neither a result of the activity of carnivores nor is it a gravity-deposited entrance facies deposit since both of these tend to be poorly bedded with a high initial dip.

It is proposed that this unit was originally deposited as entrance facies deposits, containing bones (either from pit traps or carnivore dens), which slumped (or were washed by flood pulses) into shallow still ponds of water in the lower parts of the cave. In such conditions a slurry could be produced that would be viscous enough to support and align the bone fragments. Cobbles would be transported to the ponds by sliding and rolling.

Any taphonomic or stratigraphic relationships that might have existed between bone material in the original entrance facies deposits would have been destroyed during their subsequent transport and re-deposition.

C.3. *Upper red unit*

The upper red unit is an entrance facies deposit very similar to the lower red unit. It attains a thickness of 6.6 m in Mitchell Cave where it is sparsely cemented and contains a few bone and tooth fragments.

Entrance Facies

The term 'entrance facies' (Kukla and Lozek, 1958) is applied here to poorly sorted sediments deposited in cave entrances and talus cones largely by the action of gravity and rain wash. The upper and lower red units are good examples of this type of deposit.

Red entrance facies deposits are found in the majority of the Wellington Caves and were considered to be part of the same unit by Frank (1971). In the type section in Mitchell Cave the upper red unit conformably overlies the Bone Cave breccia unit, however, the stratigraphic positions of similar sediments in other caves referred by Frank (1971) to his 'Unit 3.R' are far from certain. Frank reported rabbit bone in some sediments in Bone Cave while the author has found dog and human skeletal material in the entrance facies deposits of Triplet Cave. Entrance facies are currently being deposited as talus cones in the Bat Chamber of the Phosphate Mine and as rain wash in Gas Pipe Cave.

D. *Strata with Uncertain Relationships*

Two sequences exposed in the Phosphate Mine cannot be correlated with the stratigraphic scheme outlined above. In the Main Drive of the Phosphate Mine (locality 9, Fig. 8) entrance facies deposits are overlain by conglomerate (Fig. 13A) consisting of irregularly arranged subangular clasts, up to 16 mm across, in a tan coloured matrix (Fig. 9**D**). The clasts are laminated clays and phosphorites while the matrix (USGD 61707, Fig. 13) is composed of sand-sized quartz grains in a fine phosphatic mud. Some clasts of amorphous phosphorite are recrystallizing into fine acicular crystals of apatite. This conglomerate is probably the result of slumping of cave-derived detritus, the clasts being produced by breakdown of cave passages ex-

level indicate a significant period of phreatic speleogenesis and surface erosion between the deposition of the Phosphate Mine Beds and that of the Mitchell Cave Beds. In their models for speleogenesis, Colditz (1943), Frank (1971), and Francis (1973) considered that the last time the water table was high enough to place the caves in the phreatic zone was during the Pliocene or Miocene. If this is the case then the unconformity must be at least Late Pliocene in age and the Phosphate Mine Beds a Tertiary deposit.

Preliminary palaeontological evidence as to the age of the Big Sink unit is equivocal. Some small tooth fragments extracted from it (SUP 14972) are from rodents and marsupials (J. A. Mahoney, pers. comm). These two groups have Australian histories extending into the Tertiary (Archer and Bartholomai, 1978) and more work is required before an age can be assigned to this material. L. Dawson (pers. comm.) has collected remains of *Protemnodon* sp. from the unit which, on the basis of present knowledge, are Late Pliocene to Pleistocene in age. Should the Big Sink unit be found to be Pleistocene in age the caves must have been in the phreatic zone more recently than Colditz, Frank, or Francis have inferred.

Conclusions

Wellington Caves were excavated by groundwater solution under low energy phreatic (nothephreatic) conditions which persisted while the phosphatic rim rock and lower units of the Phosphate Mine Beds were deposited. The level of the water table was not constant during this period and desiccation features in the laminite unit and the graded-bedded unit were produced at times of low water.

Following deposition of the graded-bedded unit a significant lowering of the water table took place leading to large scale mud cracking and the deposition of speleothem. After this phreatic conditions were again established and the conglomerate and phosphorite units were deposited. The water table again fell and vadose conditions were established in Big Sink, Bone Cave and the Phosphate Mine. Entrance facies deposits accumulated forming the Big Sink unit.

Following deposition of the Big Sink unit the water table rose significantly and a second period of cave excavation was initiated. This formed new caves within the Phosphate Mine Beds and enlarged those in bedrock. A period of surface erosion that planed off the surface, exposing the Big Sink unit, occurred at the same time as the caves were enlarged.

Vadose conditions were again established and the Mitchell Cave Beds deposited. The lower red unit and the upper red unit were deposited under dry vadose conditions similar to those existing in the caves today while the Bone Cave breccia unit was deposited under wetter conditions.

Acknowledgements

References

ARCHER, M., and BARTHOLOMAI, A., 1978. — Tertiary mammals of Australia: a synoptic view. *Alcheringa* 2(1): 1-19.

BOUMA, A. H., 1962. — *Sedimentology of some Flysch Deposits.* Amsterdam: Elsevier.

BULL, P. A., 1977. — Laminations or varves? Processes and mechanisms of fine grained sediment deposition in caves. *Proc. 7th. Inter. Speleol. Congress, Sheffield:* 86-89.

CARNE, J. E., 1919. — Phosphate deposits in limestone caverns in New South Wales. *Mineral Resour. N.S.W.* 25: 393-400.

COLDITZ, M. J., 1943. — The physiography of the Wellington district, N.S.W. *J. Proc. Roy. Soc. N.S.W.* 76: 235-251.

DAWSON, L., 1982. — Marsupial fossils from Wellington Caves, N.S.W. Kensington: University of New South Wales, Ph.D. thesis, unpubl.

DUGAN, K. G., 1980. — Darwin and *Diprotodon:* the Wellington Caves fossils and the law of succession. *Proc. Linn. Soc. N.S.W.* 104(4): 265-272.

FRANCIS, G., 1973. — Evolution of the Wellington Caves landscape. *Helictite* 11(4): 79-91.

FRANK, R., 1971. — The clastic sediments of the Wellington Caves, New South Wales. *Helictite* 9(1): 3-26.

GROVER, N. C., and HOWARD, C. S., 1938. — The passage of turbid water through Lake Mead. *Amer. Soc. Civil Eng. Trans.* 103: 720-790.

JENNINGS, J. N., 1977. — Caves around Canberra. *Proc. 11th. Biennial Conf. Aust. Speleol. Fed.,* Canberra: 79-95.

KUKLA, J., and LOZEK, V., 1958. — K problematice vyzkumu jeskynrich vypini. *Cesk. Kras.* 11: 19-83.

LANE, E. A., and RICHARDS, A. M., 1963. — The discovery, exploration and scientific investigation of the Wellington Caves, N.S.W. *Helictite* 2(1): 1-53.

LUNDELIUS, E. L. Jr., 1966. — Marsupial carnivore dens in Australian caves. *Stud. Speleol.* 1: 174-180.

OSBORNE, R. A. L., 1978. — Structure, sediments and speleogenesis at Cliefden Caves, New South Wales. *Helictite* 16(1): 3-32.

——, 1982. — Cave deposits of Wellington Caves, N.S.W. Sydney: University of Sydney, M.Sc. thesis, unpubl.

——, ALLAN, T. L., ALLAN, A. D., and STEWART, B., 1981. — Extensions to Lime Kiln Cave, Wellington Caves, N.S.W. *Sydney University Speleo. Soc. Bull.* 21(5): 60-63.

PIEARCE, T. G., 1975. — Observations on the flora and fauna of Ingleborough Cavern, Yorkshire. *Trans. Brit. Cave Res. Assn.* 2(3): 107-115.

RAMSAY, E. P., 1882. — Curator's report on the exploration of caves and rivers of N.S.W. *Votes and Proceedings of the Legislative Assembly N.S.W. 1882.* 5:45.

STRUSZ, D. L., 1965. — A note on the stratigraphy of the Devonian Garra Beds of N.S.W. *J. Proc. Roy. Soc. N.S.W.* 93: 85-90.

TRICKETT, O., 1900. — Wellington Caves. *Ann. Rept. Dept. Mines N.S.W.* 1900: 200.

——, 1906. — *The Wellington Caves.* Sydney: N.S.W. Govt. Tourist Department.

WALKER, R. G., 1975. — Generalized facies models for resedimented conglomerates of turbidite association. *Bull. Geol. Soc. Amer.* 86: 737-748.